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(54) **SYSTEM AND METHOD FOR HYDROGEN EXFOLIATION GETTERING**

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(51) **Int. Cl.**
***H01L 21/30*** (2006.01)

(52) **U.S. Cl.** ....................................... **438/473**; 438/458

(58) **Field of Classification Search** ................ 438/473, 438/458

See application file for complete search history.

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(57) **ABSTRACT**

A hydrogen (H) exfoliation gettering method is provided for attaching fabricated circuits to receiver substrates. The method comprises: providing a Si substrate; forming a Si active layer overlying the substrate with circuit source/drain (S/D) regions; implanting a p-dopant into the S/D regions; forming gettering regions underling the S/D regions; implanting H in the Si substrate, forming a cleaving plane (peak concentration (Rp) H layer) in the Si substrate about as deep as the gettering regions; bonding the circuit to a receiver substrate; cleaving the Si substrate along the cleaving plane; and binding the implanted H underlying the S/D regions with p-dopant in the gettering regions, as a result of post-bond annealing.

**17 Claims, 7 Drawing Sheets**

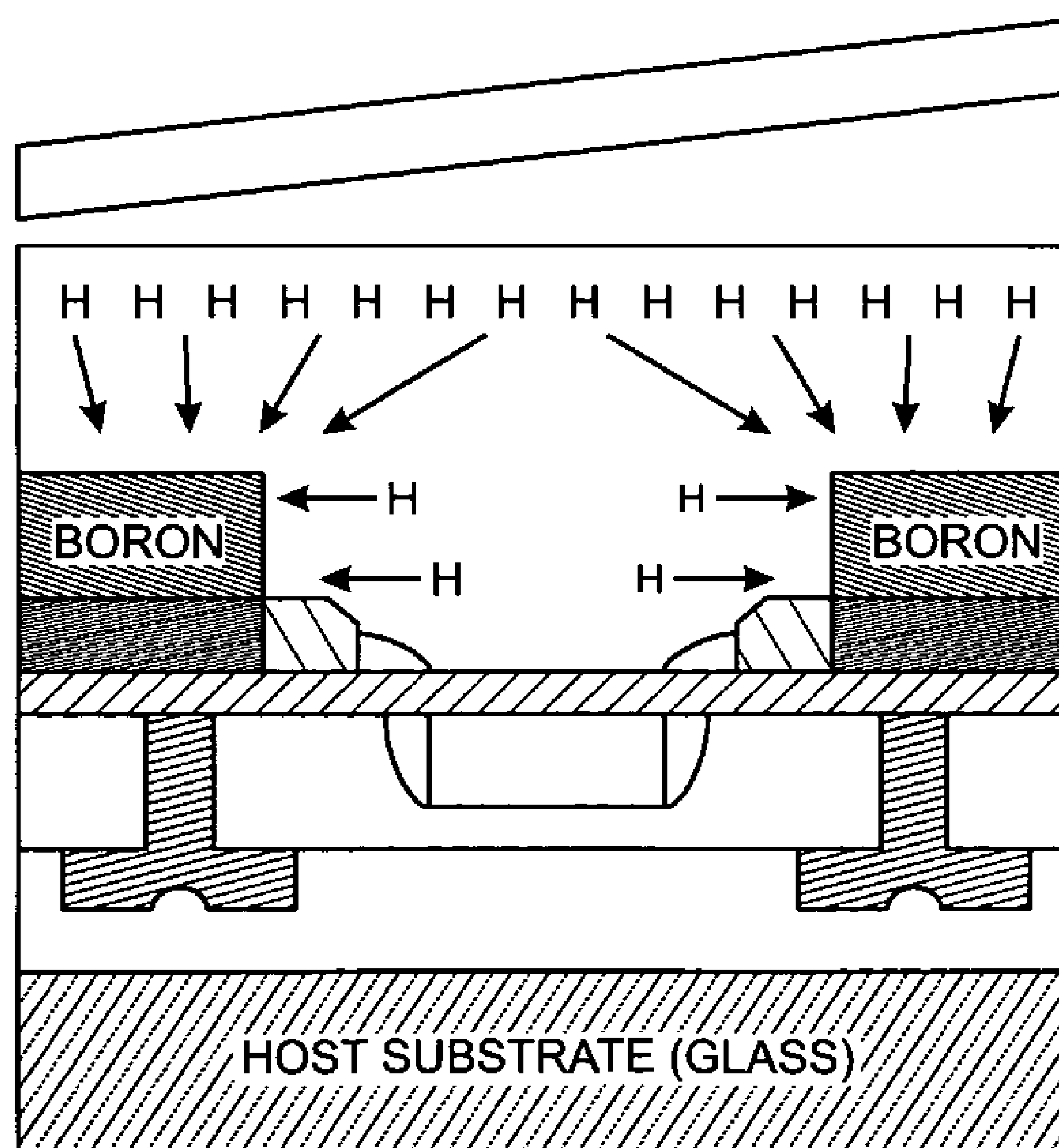

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Fig. 1
*(PRIOR ART)*

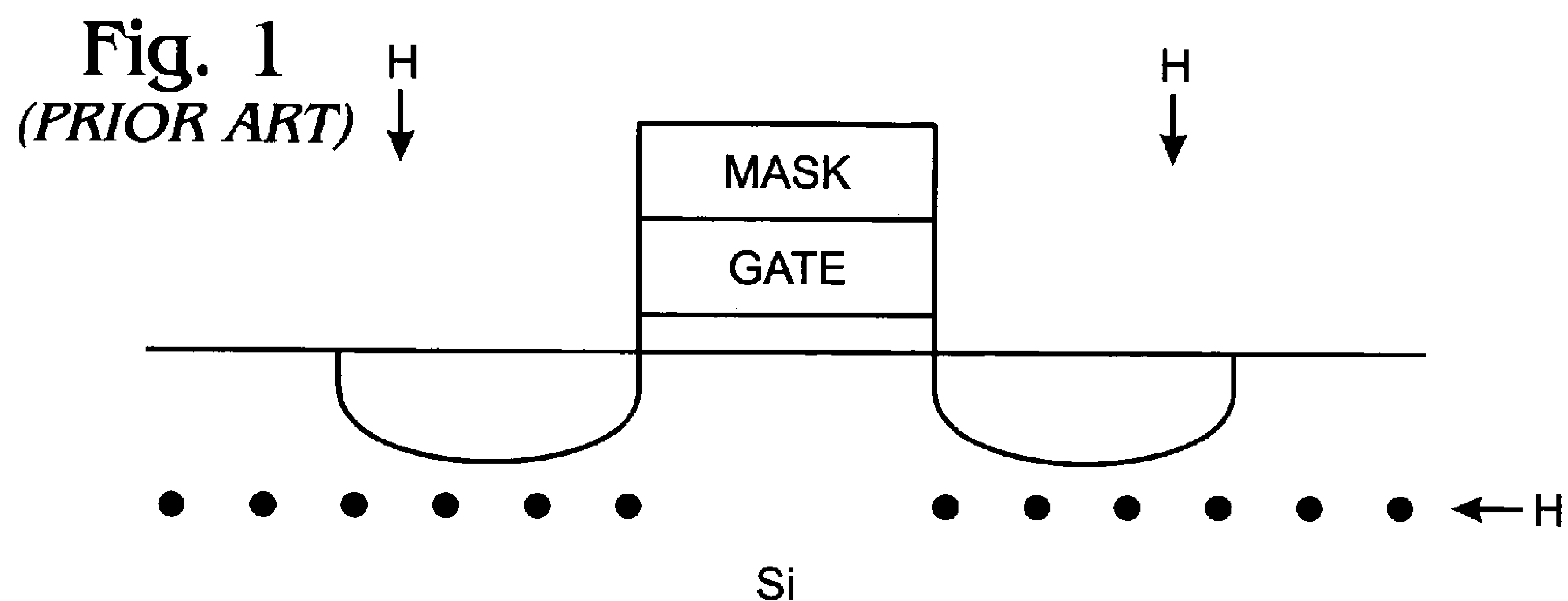



Fig. 2A

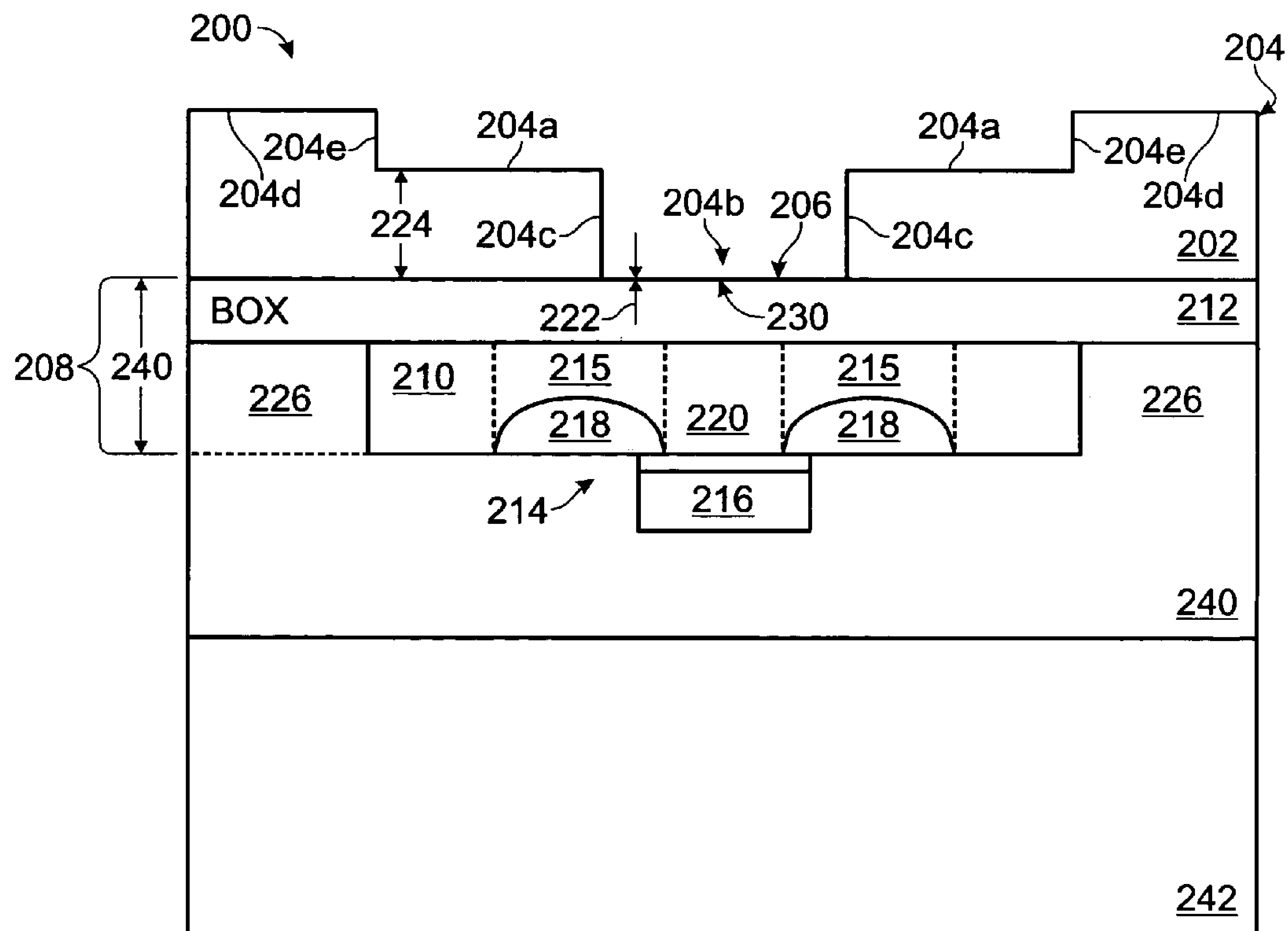


Fig. 2B

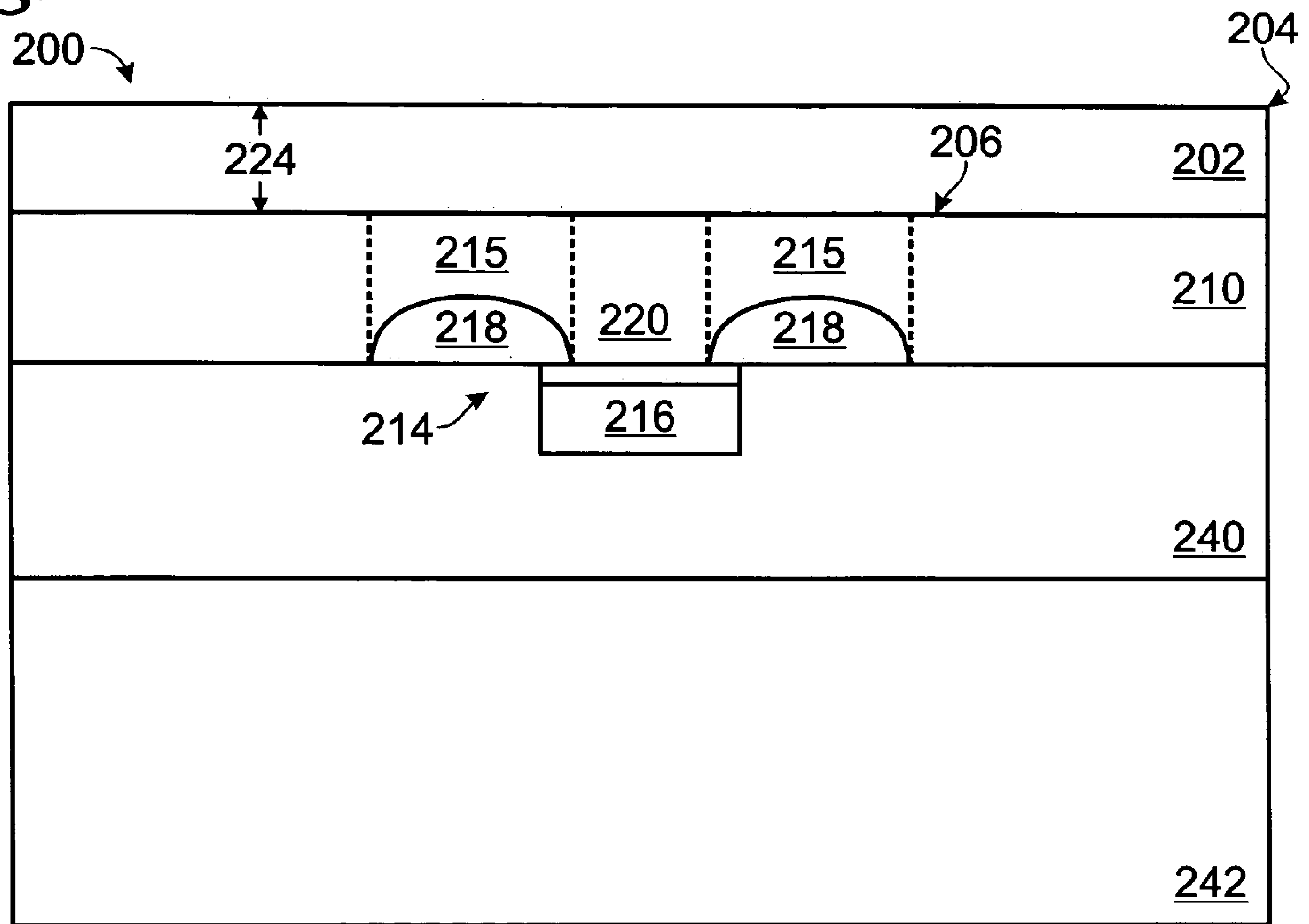



Fig. 3A

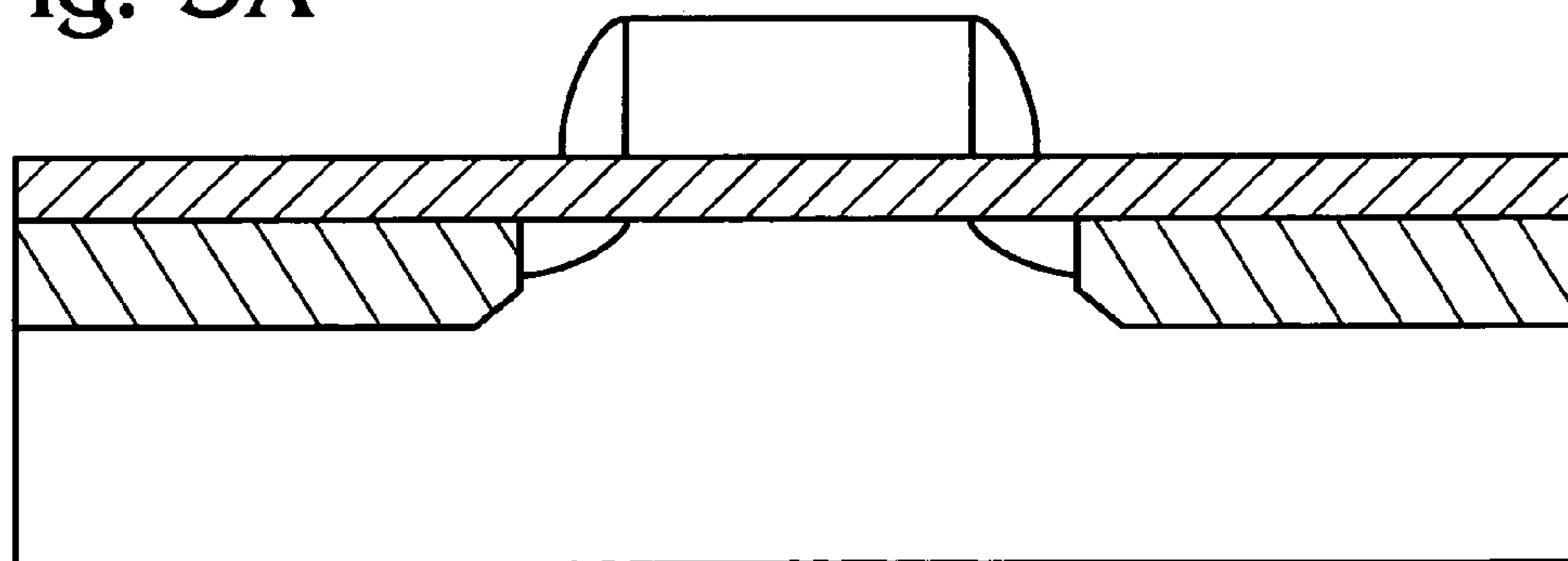


Fig. 3B

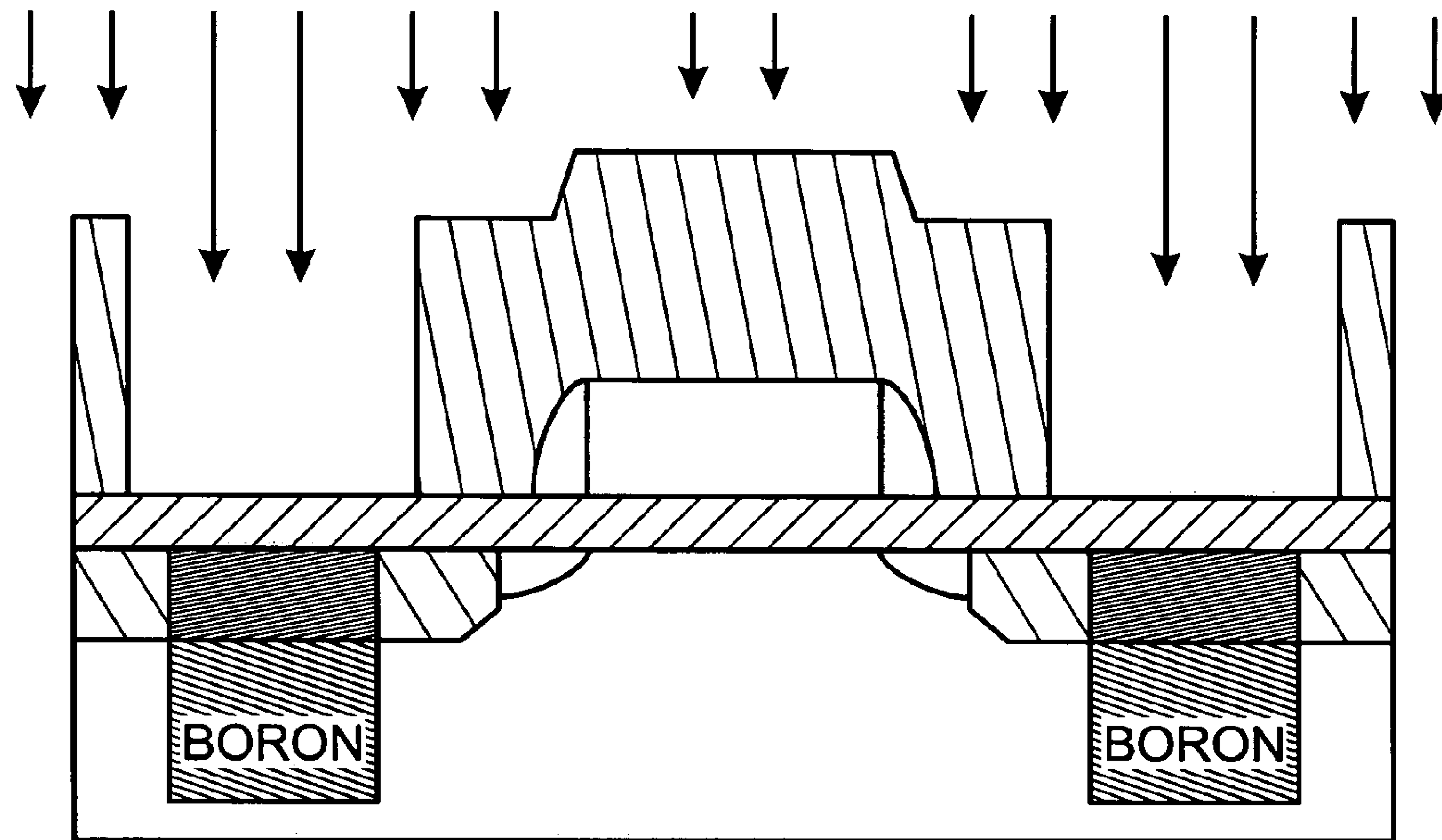



Fig. 4A

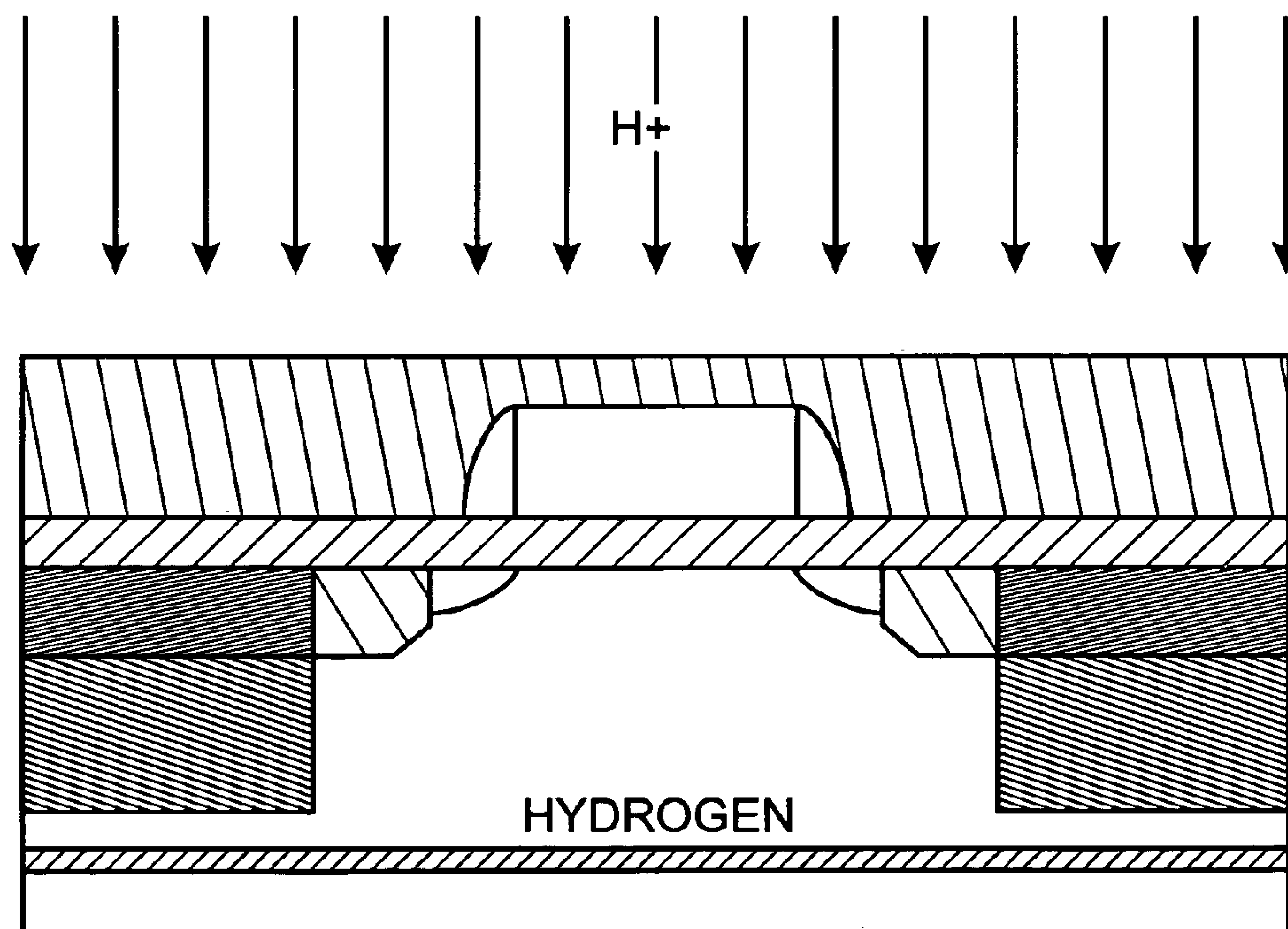


Fig. 4B

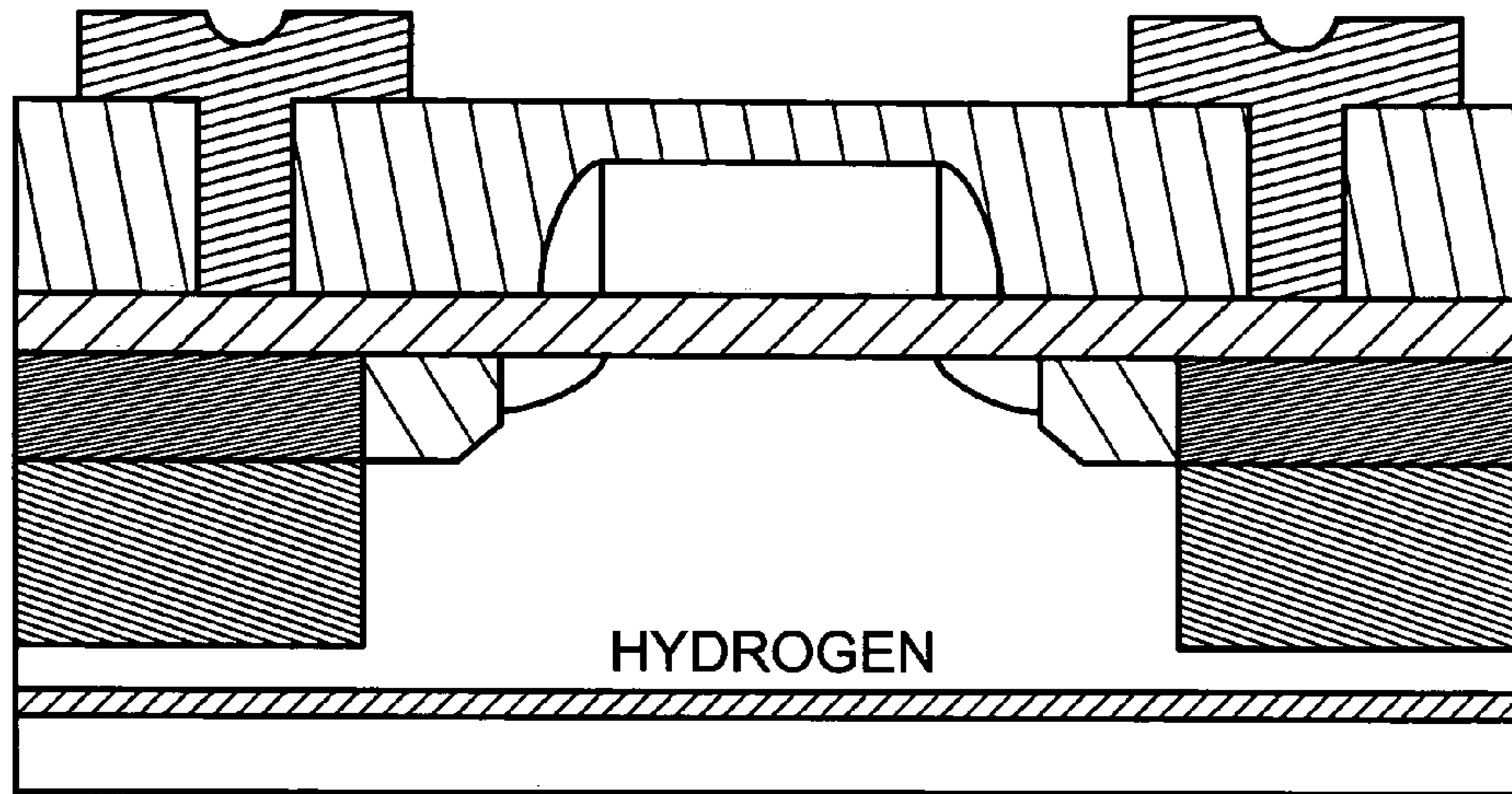



Fig. 5A

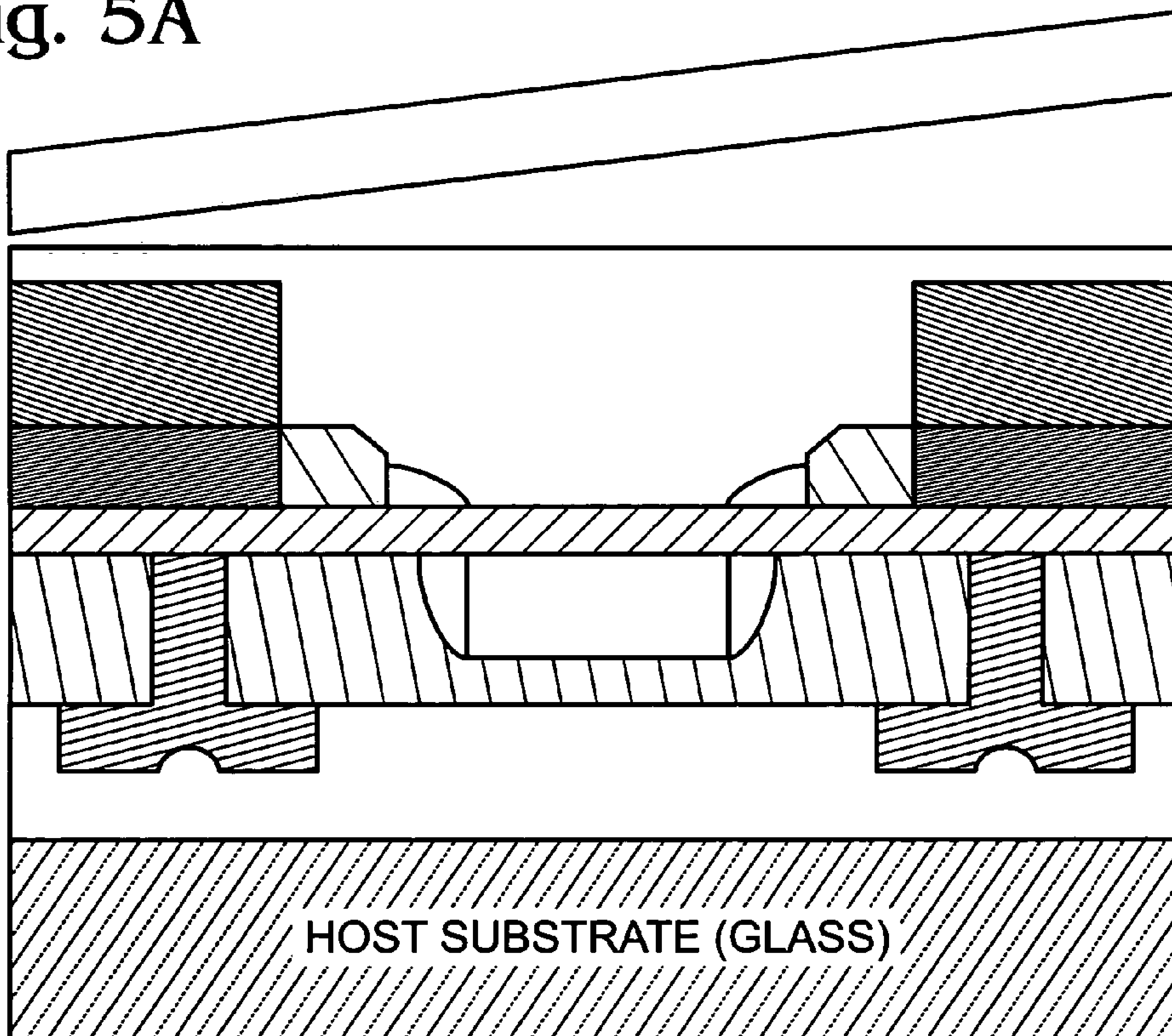


Fig. 5B

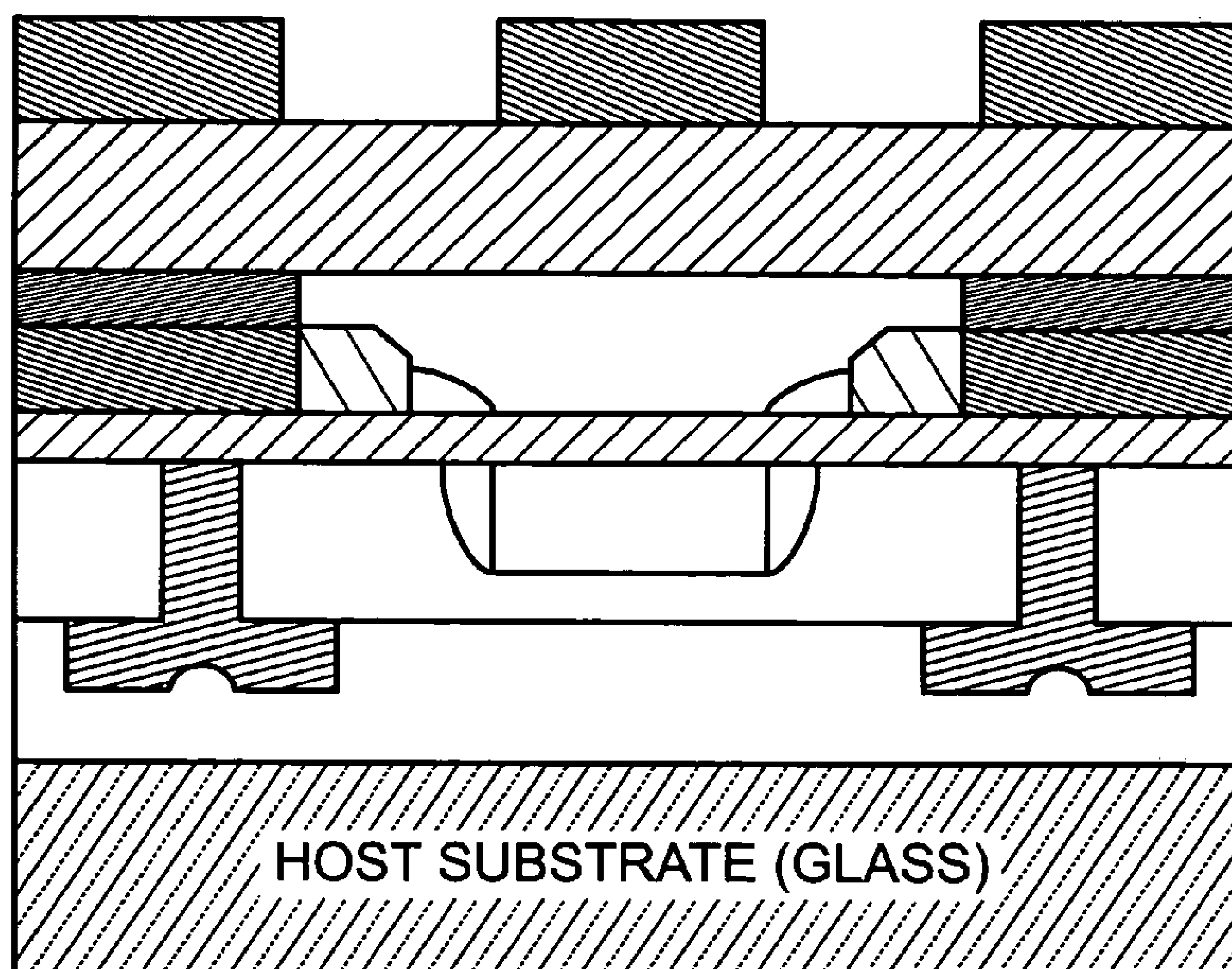



Fig. 6

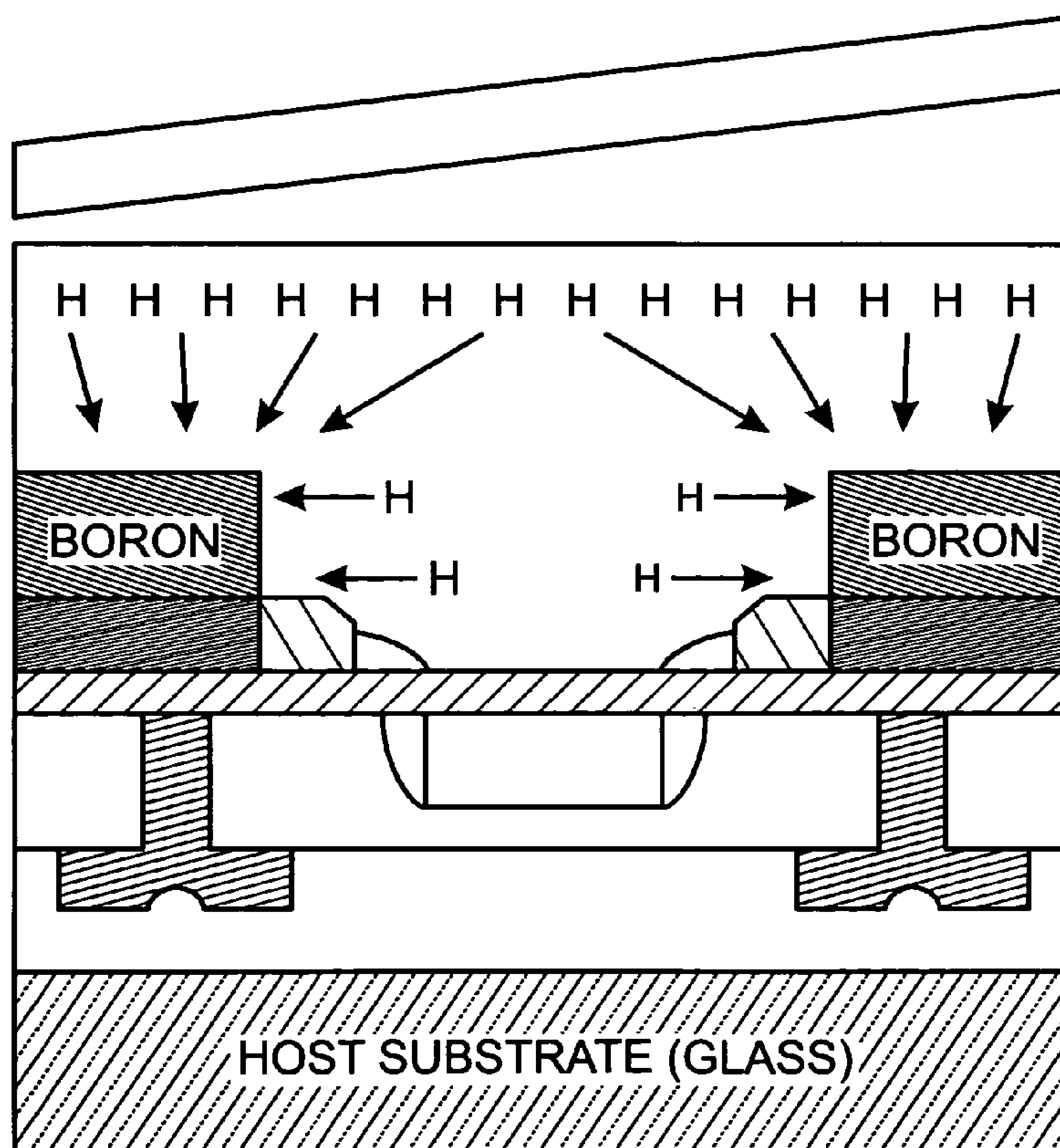
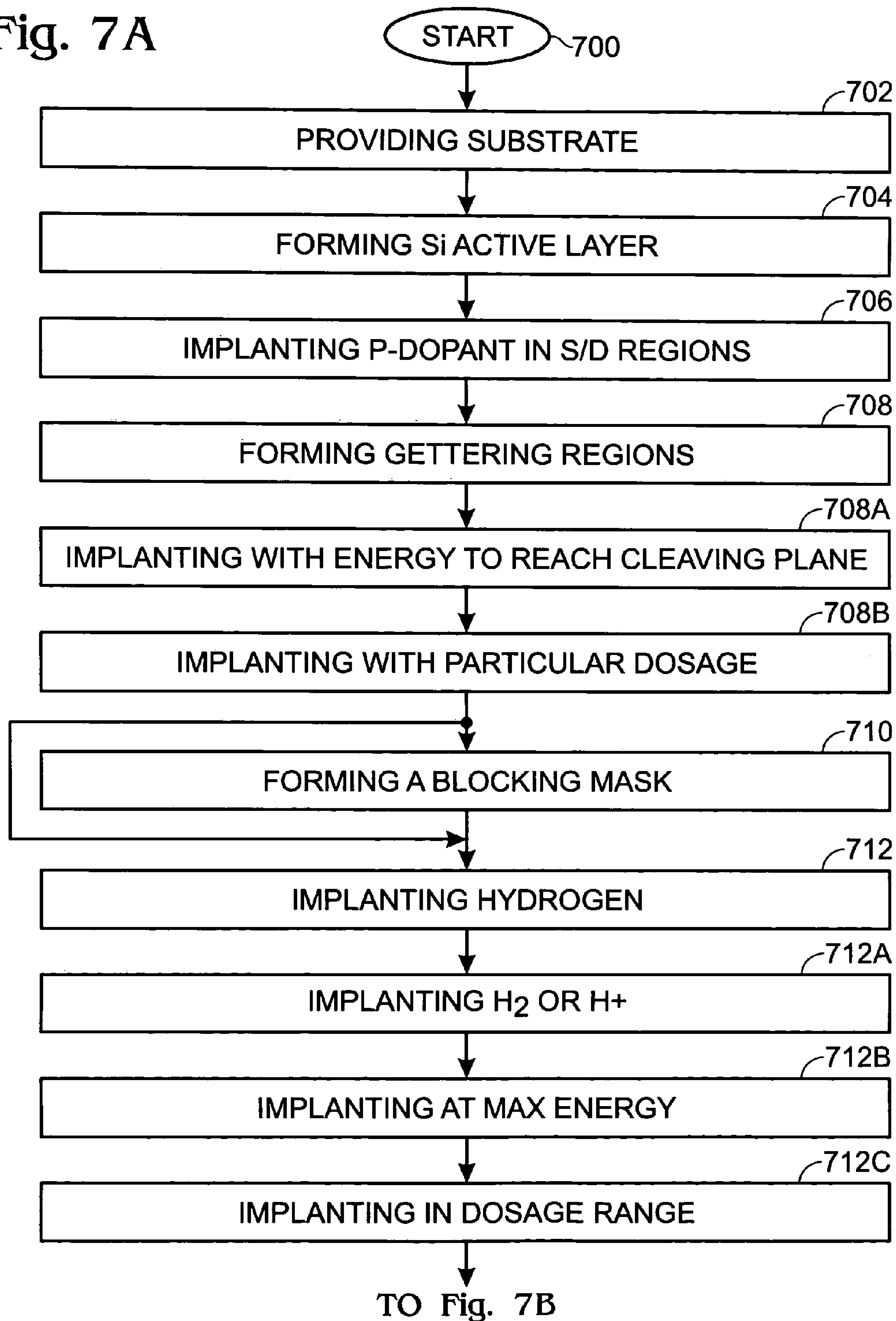


Fig. 7A



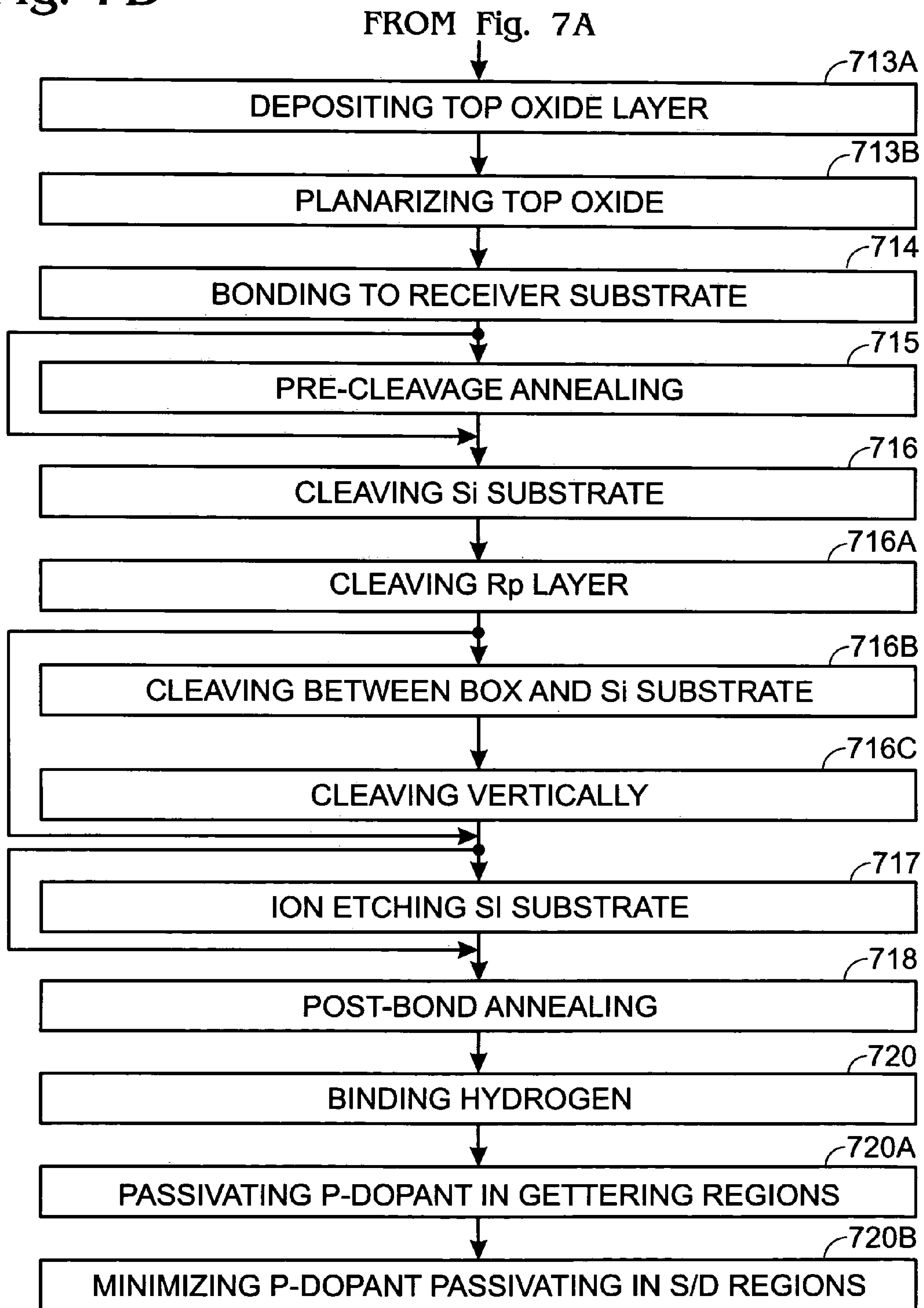


Fig. 7B
FROM Fig. 7A
713A
DEPOSITING TOP OXIDE LAYER
713B
PLANARIZING TOP OXIDE
714
BONDING TO RECEIVER SUBSTRATE
715
PRE-CLEAVAGE ANNEALING
716
CLEAVING Si SUBSTRATE
716A
CLEAVING Rp LAYER
716B
CLEAVING BETWEEN BOX AND Si SUBSTRATE
716C
CLEAVING VERTICALLY
717
ION ETCHING SI SUBSTRATE
718
POST-BOND ANNEALING
720
BINDING HYDROGEN
720A
PASSIVATING P-DOPANT IN GETTERING REGIONS
720B
MINIMIZING P-DOPANT PASSIVATING IN S/D REGIONS

# SYSTEM AND METHOD FOR HYDROGEN EXFOLIATION GETTERING

## RELATED APPLICATIONS

This application is a continuation-in-part from a pending application entitled SYSTEM AND METHOD FOR HYDROGEN EXFOLIATION, invented by Droes et al, filed on Sep. 28, 2004, Ser. No. 10/953,938, which is incorporated herein by reference.

## BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention generally relates to integrated circuit (IC) fabrication and, more particularly, to a method for transferring partially completed circuits from silicon substrates, to temperature sensitive substrates, for liquid crystal display (LCD) applications.

2. Description of the Related Art

There is broad agreement in the flat panel display (FPD) industry that system-on-glass (SOG) technology is a natural evolutionary step for flat panel displays, especially for mobile devices. In fact, SOG is a natural confluence of display and microprocessor evolution because integration is a proven solution for greatly reducing costs, while improving the compactness and reliability of electrical systems.

Display modules have received some enhanced functionality, like display drivers and analog-to-digital converters, thanks to low-temperature polysilicon (LTPS) technology. Conventionally, the best means for achieving adequate LTPS performance for SOG devices at a competitive cost is the crystallization of a thin amorphous layer of silicon with a laser beam. Unfortunately, this approach remains relatively expensive, even years after being introduced to LCD production. Moreover, even if polysilicon thin film transistors (TFTs) can be efficiently produced using this method, it is unlikely that they have sufficient capability to realize some sophisticated functions like CPU operations, digital driver LCDC, digital-to-analog converter (DAC), memory, graphical controller, wireless, MPU, and digital signal processing. Finally, the steadiness of drive currents produced by poly-Si TFTs may be inadequate for new technologies such organic electroluminescent displays.

There are two major problems that prevent the integration of the above-mentioned functions into integrated LCD products. One is the film quality, and the other is the design limitations associated with glass substrates. The poly-Si created by laser annealing consists of numerous small grains, with a typical size of less than 1 micron. Each grain is oriented differently and surrounded by grain boundaries, which cause degradation in the resultant device characteristics. Further, the poly-Si TFT device characteristics are not uniform. The problem with the small, non-uniform grain size is compounded by the fact the energy-producing operations that can address this problem are limited by the sensitivity of LCD substrates to high temperatures.

In short, the convolution between cost and performance of polysilicon devices still pales compared to that of single-crystal silicon (c-Si). The trouble is in creating quality thin films of c-Si on transparent or flexible substrates, which usually are made of materials other than silicon. Other solutions to this hybrid field problem include Fluidic-Self-Assembly™ (FSA) by Alien Technology. FSA works fairly well for plastic substrates and semiconductor blocks thicker than 50 microns. Unfortunately, FSA placement depends on random probability and gravity. Because the probability of successful placement is small (<<20%), a large amount of blocks are needed. Also, as the blocks get smaller, Brownian motion becomes more disruptive to precise placement and more time is required for settlement. Finally, if glass substrates are desired, then another problem is the efficient etching of precise-sized holes. Other rapid assembly techniques, like capillary self-assembly, still require fluid, which usually demands use of surfactants, and remain susceptible to Brownian motion.

SOITEC and other researchers have developed and refined a means of efficiently creating thin films of c-Si by ion-cutting with a high dose hydrogen implantation. In related work, Joly et al. have extended the ion-cutting process (Smart-Cut) to produce devices on one substrate, and transfer these devices to a different substrate. While their work describes a process for transferring the devices, there is little discussion regarding the impact of high dose hydrogen implantation on device performance. It is acknowledged by many that the required large doses of hydrogen (~$5e^{16}$ atoms/$cm^2$) can result in highly defective regions in the transferred silicon films.

FIG. **1** is a diagram of a hydrogen-induced cleaving process using a hydrogen blocking mask (prior art). To address some of the problems associated with the use of hydrogen, Bruel et al., describe the use of a blocking mask to protect active silicon regions from damage during the hydrogen implant. A blocking mask adds an extra step to the fabrication process. However, if hydrogen is allowed to diffuse into the substrate near the channel areas, then dopants in the channel and source/drain regions may bind with the hydrogen and impact the performance of the transistor. Therefore, conventional processes have not proved to be practical for large-scale fabrication processes, or for the transfer of very large active Si areas, such as VLSI circuits with a plurality of blocked areas.

It would be advantageous if an improved substrate cleaving processes were developed that minimized the detrimental effects of hydrogen.

## SUMMARY OF THE INVENTION

This application generally relates to processes for fabricating single-crystal silicon devices, cleaving the devices from a substrate, and placing them on glass substrates suitable for making hybrid devices. More particularly, the application relates to the transfer of partially completed VLSI circuits from single-crystal silicon substrates to glass panels for the production of flat panel displays. The process can be used to place partially completed VLSI crystalline silicon devices onto non-silicon substrates for the purpose of making large area devices, especially display systems, such as a display matrix, complementary signal devices, and control circuitry.

This application addresses the problems associated with presence of hydrogen that may remain as a result of the substrate cleaving process. The problem is solved by implanting a region of p-dopant near the active regions, to act as a hydrogen gettering layer. Furthermore, any hydrogen in the channel region due to implantation, though at a lower concentration than at the cleaving plane, is also gettered by p-dopant near the S/D regions. As such, the hydrogen concentration in the channel is lower than in other regions where p-dopant is implanted. The decreased level of hydrogen in these areas reduces the extent of p-dopant deactivation.

Accordingly, a hydrogen (H) exfoliation gettering method is provided for attaching fabricated circuits to receiver

substrates. The method comprises: providing a Si substrate; forming a Si active layer overlying the substrate with circuit S/D regions; implanting a p-dopant into the S/D regions; forming p-dopant gettering regions underling the S/D regions; implanting H in the Si substrate, forming a cleaving plane (peak concentration (Rp) H layer) in the Si substrate about as deep as the p-dopant gettering regions; bonding the circuit to a receiver substrate; cleaving the Si substrate along the cleaving plane; and binding the implanted H underlying the S/D regions with p-dopant in the p-dopant gettering regions, as a result of post-bond annealing. More specifically, binding the implanted H with p-dopant in the gettering regions includes: passivating p-dopant in the gettering regions; and minimizing the passivation of p-dopant in the S/D regions.

Typically, forming a Si active layer overlying the substrate includes forming a channel region with p-dopant dopant, interposed between the S/D regions. Then, forming gettering regions includes forming gettering regions adjacent the channel region, minimizing the passivation of p-dopant in the channel region.

Additional details of the above-described method and an active Si device cleaved from a silicon substrate are provided below.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a diagram of a hydrogen-induced cleaving process using a hydrogen blocking mask (prior art).

FIG. **2**A is a partial cross-sectional view of an active Si device cleaved from a silicon-on-insulator (SOI) substrate.

FIG. **2**B is a partial cross-sectional view of an active Si device cleaved from a silicon substrate.

FIGS. **3**A through **5**B illustrate steps in the formation of an active device cleaved from a Si substrate, having H gettering regions.

FIG. **6** is a partial cross-sectional view of the hydrogen gettering process.

FIGS. **7**A and **7**B are flowcharts illustrating a hydrogen exfoliation gettering method for attaching fabricated circuits to receiver substrates.

## DETAILED DESCRIPTION

FIG. **2**A is a partial cross-sectional view of an active Si device cleaved from a silicon-on-insulator (SOI) substrate. The active Si device **200** comprises a Si substrate **202** with a cleaving plane surface **204** and a bottom surface **206**. A SOI substrate **208** includes a buried oxide layer (BOX) between a Si active layer **210** and Si substrate bottom surface **206**. A circuit **214** is formed in the Si active layer **210**. P-dopant gettering regions **215**, referred to herein as gettering regions, are formed in the Si active layer **210**, underlying the S/D regions. As shown, the circuit **214** in the Si active area **210** is a transistor or TFT. The TFT **214** includes a gate **216**, channel region **220**, and source/drain (S/D) regions **218** adjacent the channel region **220**. Alternately but not shown, the circuit **214** in the Si active layer **210** can be any CMOS circuit or VLSI device (with many TFT or CMOS circuits) using a p-doped semiconductor material.

The Si substrate cleaving plane surface **204** includes a first thickness surface **204***a* in areas underlying the S/D regions **218**, a second thickness surface **204***b*, where the second thickness is less than the first thickness, in areas underlying the channel region **220**. The cleaving plane surface **204** also includes vertical plane surfaces **204***c* formed between the areas of first and second thickness surfaces. The gettering regions **215** are formed in the Si active layer **210**, between the first thickness surface **204***a* and the S/D regions **218**. The Si substrate cleaving plane first thickness **224** is in the range of 20 to 1000 nanometers. The Si substrate cleaving plane second thickness **222** is in the range of 0 to 1000 Å. Also shown is a third thickness surface **204***d* underlying the field regions **226**. Vertical plane surfaces **204***e* are formed between the areas of the second and third thickness surfaces **204***b* and **204***d*. As shown, the second thickness **222** is approximately zero. That is, the second thickness surface **204***b* is formed on the surface **230** of the BOX.

The Si substrate first thickness surface **204***a* includes a peak concentration of hydrogen (H), and the second thickness surface **204***b* includes a minimum concentration of H. The S/D regions **218** and channel region **220** include a p-dopant. That is, the S/D regions **218** and channel regions **220** are p-doped. The gettering regions **215** include H-passivated p-dopant. The p-dopant may be boron (B), gallium (Ga), indium (In), or aluminum (Al). Note, the p-dopant in the S/D regions **218** and channel **220** need not necessarily be the same p-dopant as is used to form gettering regions **215**. In one aspect, the gettering regions **215** include a p-dopant dosage of in the range of $1\times10^{19}$ to $5\times10^{20}$ atoms/cm$^3$. The Si substrate first thickness surface **204***a* has a peak concentration of hydrogen in the range of $5\times10^{15}$ to $5\times10^{17}$.

Any concentrations of H that remain in the Si active layer **210** after the cleaving process, react with the p-dopant in the gettering regions **215**. This prevents the H from reacting with the p-dopant in the S/D regions **218** and the channel region **220**. Substantially less H exists in the active Si layer **210** underlying the channel region **220** because of the blocking effect of the gate **216**. Although not shown, a temporary H blocking mask is used during the H implant, overlying the channel region **220** (and gate **216**), similar to the mask shown in FIG. **1**.

A planarized oxide layer **240** overlies the active Si layer circuit **214**. A receiver substrate **242**, made from a material such as glass, plastic, quartz, or metal foil is directly bonded to the oxide layer **240**.

FIG. **2**B is a partial cross-sectional view of an active Si device cleaved from a silicon substrate. For example, a bulk Si substrate may be used. A Si substrate **202** has a cleaving plane surface **204** and a bottom surface **206**. An active layer **210** overlies the Si substrate bottom surface **206**. A circuit **214** is formed in the Si active layer **210**. Again, the circuit **214** is shown to be a TFT or transistor. However, the circuit can also represent a portion of a CMOS or VLSI circuit. Gettering regions **215** are formed underling the S/D regions, in the Si active layer. Thus, the circuit **214** in the Si active area **210** includes a channel region **220**, and source/drain (S/D) regions **218** adjacent the channel region **220**. The gettering regions **215** are formed in the Si active layer **210** between the cleavage plane **204** and the S/D regions **218**.

The S/D regions **218** and channel region **220** include a p-dopant, and the gettering regions **215** include H-passivated p-dopant. Alternately stated, the gettering regions **215** include p-dopant-passivated hydrogen. A planarized oxide layer **240** overlies the active Si layer circuit **214**. A receiver substrate **242**, made from a material such as glass, plastic, quartz, or metal foil is directly bonded to the oxide layer **240**.

The Si substrate has a thickness **224** between the cleaving plane **204** and the bottom surface **206** that is in the range of 20 to 1000 nanometers. The gettering regions **215** include a dosage of p-dopant in the range of $1\times10^{19}$ to $5\times10^{20}$ atoms/

$cm^3$. The Si substrate cleavage plane **204** has a peak concentration of hydrogen in the range of $5\times10^{15}$ to $5\times10^{17}$. As in the device of FIG. **2**A, the gettering regions **215** include a p-dopant such as boron, gallium, indium, or aluminum.

## FUNCTIONAL DESCRIPTION

The fabrication of single-crystal silicon devices on glass substrates, using a hydrogen cleaving process, may result in an interaction of hydrogen and boron in the final devices. For example, a silicon wafer is first implanted with hydrogen so that the peak concentration (Rp) is located well below the silicon surface, for example 0.5 to 1.0 microns (um). The silicon substrate is then bonded directly to a glass substrate. When the bonded pair is heated (>400° C.), hydrogen forms small platelets and causes the silicon to exfoliate in a single layer at the Rp.

Using this method to transfer partially completed CMOS devices to glass substrates, it is possible that hydrogen may interact with the p-dopant in the devices to cause device failure. Specifically, after transferring the devices to the glass substrate, a high temperature anneal is required (~650° C.). This causes diffusion of the remaining hydrogen in the silicon, and interaction with a p-dopant such as boron. Boron is noted to effectively getter hydrogen. Conventionally, when hydrogen and boron interact, the hydrogen effectively de-activates the boron dopants in the channel regions and source/drain regions.

FIGS. **3**A through **5**B illustrate steps in the formation of an active device cleaved from a Si substrate, having H gettering regions. Details of the hydrogen exfoliation and gettering process follow. FIGS. **3**A and **3**B are partial cross-sectional views following the performance of Steps 1 and 2, respectively. 1. Begin with a conventional MOSFET process, up to the gate and source/drain formation. HALO and lightly doped drain (LDD) processes may be required for short channel length (L) devices.

2. Next, implant boron (for example) into selected areas of the S/D regions. For N-channel devices, the concentration of boron will be lower than the N+ concentration of the source/drain regions. This ensures that the source/drain regions retain their N+ characteristics. The concentration of boron in the implanted region ranges from 1E19 atoms/$cm^3$ to 5E20 atoms/$cm^3$. The lower limit of boron implantation is determined by the extent of hydrogen gettering. Since N+ region formation requires N+ impurity concentrations sufficiently higher than that of boron, the upper limit of B implantation is determined by N+ source/drain formation.

FIGS. **4**A and **4**B are cross-sectional views following the performance of Steps 3 and 4, respectively.

3. Deposit additional $SiO_2$ layer and flatten the surface. Implant H+ slightly deeper than boron.

4–5. After metal layer formation (STEP4), bond to the host substrate (such as glass substrate) and cleave at the hydrogen-implanted interface by annealing. (STEP5)

FIGS. **5**A and **5**B are cross-sectional views following the completion of Steps 5 and 6, respectively.

6. The Si layer is thinned down to remove the damaged region of the H+ implantation. Interlayer dielectric material is deposited (such as $SiO_2$), contact holes are formed, and the TFT structure is completed.

FIG. **6** is a partial cross-sectional view of the hydrogen gettering process. As mentioned earlier, hydrogen in the channel region causes a degradation of the device characteristics. This includes de-activation of the channel and HALO dopants. After hydrogen implantation, most of the implanted hydrogen is located near the projected range (Rp). During the cleaving anneal, hydrogen at Rp diffuses to the channel area. In this example, the boron underlying the S/D regions acts as a gettering site for hydrogen. Furthermore, hydrogen near the channel region resulting from implantation, though at a lower concentration than the Rp H concentration, is also gettered by boron underlying the S/D regions. As such, the hydrogen concentration near the channel is low. The decreased level of hydrogen in areas near the channel and S/D regions reduces the extent of boron deactivation.

Since the device created by this invention has low hydrogen concentration in the channel area, the device performance is not degraded due to boron deactivation via hydrogen. Thus, the transferred device performs comparably to a device fabricated (but not cleaved) from a single-crystal Si substrate.

FIGS. **7**A and **7**B are flowcharts illustrating a hydrogen exfoliation gettering method for attaching fabricated circuits to receiver substrates. Although the method is depicted as a sequence of numbered steps for clarity, no order should be inferred from the numbering unless explicitly stated. It should be understood that some of these steps may be skipped, performed in parallel, or performed without the requirement of maintaining a strict order of sequence. The method starts at Step **700**.

Step **702** provides a Si substrate. Step **704** forms a Si active layer overlying the substrate with circuit source/drain (S/D) regions. Step **706** implants a p-dopant into the S/D regions. Step **708** forms p-dopant gettering regions underling the S/D regions. The p-dopant can be B, Ga, In, or Al. In one aspect, Step **708** is performed simultaneously with implanting p-dopant in the S/D regions (Step **706**). However, Steps **706** and **708** need not necessarily be performed simultaneously. Further, the dopant used in the two steps need not necessarily be the same. Alternately stated, Step **708** forms gettering regions in a Si active layer underlying a circuit formed in the Si active layer. Step **712** implants H in the Si substrate, forming a cleaving plane in the Si substrate about as deep as the gettering regions. Step **714** bonds the circuit to a receiver substrate. Step **716** cleaves the Si substrate along the cleaving plane. Step **718** post-bond anneals the Si substrate. Step **720** binds the implanted H underlying the S/D regions with p-dopant in the gettering regions. Typically, the H-binding results from the annealing in Step **718**. For example, Step **718** may anneal the Si substrate at a temperature in the range of 400 to 600 degrees C.

In some aspects, binding the implanted H with p-dopant in the B gettering regions in Step **720** includes substeps. Step **720**A passivates p-dopant in the gettering regions. Alternately stated, the p-dopant in the gettering regions passivates H. Step **720**B minimizes the passivation of p-dopant in the S/D regions.

In one aspect, forming a Si active layer overlying the substrate in Step **704** includes forming a channel region with p-dopant, interposed between the S/D regions. Then, forming gettering regions in Step **708** includes forming gettering regions adjacent the channel region, and Step **720** minimizes the passivation of p-dopant in the channel region. Alternately, forming circuit S/D regions in the Si active layer (Step **704**) includes forming a VLSI or CMOS device.

In a different aspect, forming circuit S/D regions in the Si active layer (Step **704**) includes forming a circuit at process temperatures greater than 600 degrees C. Then, Step **714** bonds the circuit to a temperature-sensitive carrier substrate such as glass, plastic, quartz, or metal foil.

In another aspect, forming a cleaving plane in Step **712** includes forming a peak concentration (Rp) H layer in the Si substrate. Then, Step **716** cleaves the Si substrate along the Rp layer. In one aspect, implanting H in the Si substrate (Step **712**) includes substeps. Step **712**A implants H in a form selected from the group including H+ and H2. Step **712**B implants at a maximum energy of 1 MeV. Step **712**C implants at a dosage in the range of $5\times10^{16}$ to $5\times10^{17}$.

In one aspect Step **713**A, following the H implanting (Step **712**), deposits a top oxide layer overlying the circuit. Step **713**B planarizes the top oxide layer. Then, Step **714** directly bonds the top oxide layer to the receiver substrate.

In another aspect, Step **715** pre-cleavage anneals the substrate. Then, Step **716** cleaves in response to pre-cleavage annealing the Si substrate. For example, in one variation Step **712** implants H in the substrate to the same depth as the furthest penetration of the gettering regions. Annealing the Si substrate in Step **715** includes annealing at a temperature in the range of 200 to 300 degrees C. Then, Step **716** cleaves in response to annealing the Si substrate. Alternately, Step **716** cleaves the Si substrate in response to a mechanical separation process (Step **715** is not performed). In one aspect, following the cleaving of the Si substrate, Step **717** using an ion etch technique, removes any remaining Si substrate material.

In another aspect, forming gettering regions in the Si substrate (Step **708**) includes substeps. Step **708**A implants p-dopant with an energy sufficient to penetrate to the level of the cleaving plane. Step **708**B implants at a dosage in the range of $1\times10^{19}$ to $5\times10^{20}$ atoms/$cm^3$.

In one aspect, providing a silicon Si substrate in Step **702** includes forming a Si-on-insulator (SOI) substrate with a buried oxide (BOX) layer. Then, Step **710** forms a (temporary) blocking mask overlying the channel region. Implanting H in the Si substrate in Step **712** includes: implanting H into the S/D regions, but not the channel region underlying the blocking mask; and following the H implantation, removing the blocking mask.

In the SOI aspect, forming a cleaving plane in the Si substrate in Step **712** includes forming a horizontal peak concentration (Rp) H layer in regions of the Si substrate underlying the S/D regions. Then, cleaving the Si substrate in Step **716** includes substeps. Step **716**A cleaves a first region along the horizontal Rp layer in the regions underlying the S/D regions. Step **716**B cleaves a second region along a horizontal interface between the BOX layer and Si substrate underlying the channel region. Step **716**C cleaves vertically between the first and second regions.

A hydrogen exfoliation gettering process and an active Si device formed from using the process have been presented. Specific process details and materials have been used as examples to illustrate the invention. However, the invention is not limited to merely these examples. Other variations and embodiments of the invention will occur to those skilled in the art.

We claim:

**1**. A hydrogen (H) exfoliation gettering method for attaching fabricated circuits to receiver substrates, the method comprising:

forming a Si-on-insulator (SOI) substrate with a buried oxide (BOX) layer;

forming a Si active layer overlying the substrate with circuit source/drain (S/D) regions;

implanting a p-dopant into the S/D regions;

forming gettering regions underling the S/D regions;

implanting H in the Si substrate, forming a cleaving plane in the Si substrate about as deep as the gettering regions, with a horizontal peak concentration (Rp) H layer in regions of the Si substrate underlying the S/D regions;

bonding the circuit to a receiver substrate;

cleaving the Si substrate along the cleaving plane by

cleaving a first region along the horizontal Rp layer in the regions underlying the S/D) regions;

cleaving a second region along a horizontal interface between the BOX layer and Si substrate underlying the channel region; and

cleaving vertically between the first and second regions; and

binding the implanted H underlying the S/D regions with p-dopant in the gettering regions.

**2**. The method of claim **1** further comprising:

performing a post-bond annealing of the Si substrate; and

wherein binding the implanted H with p-dopant in the gettering regions includes binding in response to the post-bond annealing.

**3**. The method of claim **1** wherein binding the implanted H with p-dopant in the gettering regions includes:

passivating p-dopant in the gettering regions; and

minimizing the passivation of p-dopant in the S/D regions.

**4**. The method of claim **3** wherein forming a Si active layer overlying the substrate includes forming a channel region with p- dopant, interposed between the S/D) regions;

wherein forming gettering regions includes forming gettering regions adjacent the channel region; and

wherein binding the implanted H with p-dopant in the gettering regions includes minimizing the passivation of p-dopant in the channel region.

**5**. The method of claim **1** wherein forming a circuit S/D regions in the Si active layer includes forming a circuit at process temperatures greater than 600 degrees C.; and

wherein bonding the circuit to the receiver substrate includes bonding the circuit to a temperature-sensitive carrier substrate selected from the group including glass, plastic, quartz, and metal foil.

**6**. The method of claim **1** wherein implanting H in the Si substrate includes:

implanting H in a farm selected from the group including H+ and H2;

implanting at a maximum energy of 1 MeV; and

implanting at a dosage in the range of $5\times10^{16}$ to $5\times10^{17}$.

**7**. The method of claim **1** further comprising:

following the H implanting, depositing a top oxide layer overlying the circuit;

planarizing the top oxide layer; and

wherein bonding the circuit to the receiver substrate includes directly bonding the top oxide layer to the receiver substrate.

**8**. The method of claim **2** wherein cleaving the Si substrate includes cleaving in response to a pre-cleavage annealing of the Si substrate.

**9**. The method of claim **2** wherein performing a post-bond annealing of the Si substrate includes annealing at a temperature in the range of 400 to 600 degrees C.

**10**. The method of claim **1** wherein cleaving the Si substrate includes cleaving in response to a mechanical separation process.

**11**. The method of claim **1** further comprising:

forming a blocking mask overlying the channel region; and

wherein implanting H in the Si substrate includes:

implanting H into the S/D regions, but not the channel region underlying the blocking mask; and

following the H implantation, removing the blocking mask.

**12**. The method of claim **8** wherein implanting H in the Si substrate includes implanting H in the substrate to the same depth as the furthest penetration of the gettering regions;

wherein pre-cleavage annealing the Si substrate includes annealing at a temperature in the range of 200 to 300 degrees C.; and

wherein cleaving the Si substrate includes cleaving in response to pre-cleavage annealing the Si substrate.

**13**. The method of claim **1** further comprising:

following the cleaving of the Si substrate, using an ion etch technique, removing any remaining Si substrate material.

**14**. The method of claim **1** wherein forming circuit S/D regions in the Si active layer includes forming a VLSI device.

**15**. The method of claim **1** wherein forming gettering regions in the Si substrate includes:

implanting p-dopant with an energy sufficient to penetrate to the level of the cleaving plane; and

implanting at a dosage in the range of $1\times10^{19}$ to $5\times10^{20}$ atoms/cm$^3$.

**16**. The method of claim **1** wherein forming gettering regions in the Si substrate includes forming gettering regions simultaneously with implanting p-dopant in the S/D regions.

**17**. The method of claim **1** wherein forming gettering regions underlying the S/D regions includes forming gettering regions using a p-dopant selected from the group including boron, gallium, indium, and aluminum.

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